POLYHALITE ALTERS THE UPTAKE AND PARTITIONING OF MINERAL NUTRIENTS IN CORN

BY

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THESIS

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ABSTRACT

Modern corn (*Zea mays* L.) hybrids coupled with advanced agronomic practices have led to an increased yield potential on many US corn acres, but to realize these higher yields requires a better understanding of crop nutrition. Polyhalite is a multi-nutrient fertilizer that supplies four key plant nutrients potassium, calcium, magnesium, and sulfur. Sirius Minerals, a company formed to develop and market the new fertilizer, has started to commercially produce a granulated version of polyhalite with the trade name POLY4 (0-0-14-10Ca-4Mg-19S). The granulated version of polyhalite has several unique chemical characteristics that allow for a synchronized release of each nutrient in a season-long fashion. The slow-release delivery of POLY4 is the result of the fertilizer's physical characteristics, specifically its relatively low water solubility of 27 g L^{-1} (25 °C). Until recently, polyhalite based fertilizers have not been widely offered as a commercially available products due to limited mineral supply; however, there is renewed interest in polyhalite as a broad acre fertilizer due to the recent discovery of a vast Zechstein deposit in the North Sea basin on the coast of the United Kingdom. The objective of this study was to document the pattern of uptake, partitioning, and remobilization of nutrients by corn plants fertilized with POLY4 compared to muriate of potash (MOP;0-0-60). Field studies were conducted in 2017 and 2018 comparing pre-plant applications of 75 lb $acre^{-1}$ of K_2O as MOP, 75 lb $acre^{-1}$ of K_2O as POLY4, and 75 lb $acre^{-1}$ of K_2O as a 75:25 blend of POLY4:MOP to an untreated control. Plants were sampled aboveground at the V6, V10, V14, R2, R4, and R6 growth stages, and separated into four fractions for dry weight and nutrient determination, with grain yield also measured at physiological maturity. All of the potassium fertilization treatments resulted in significantly greater above-ground dry weight accumulation compared to the unfertilized control, but season-long plant accumulations of potassium and sulfur were greater in response to all treatments containing

POLY4. Corn grain yield production was greatest for plants fertilized with POLY4 and POLY4:MOP; both of which resulted in a 6 bu $acre^{-1}$ yield increase over plants fertilized with MOP and a 7 bu $acre^{-1}$ yield increase compared those that did not receive any potassium fertilizer. Corn that did not receive any potassium fertilizer had a two-year average grain yield of 254 bu $acre^{-1}$. Differences in crop growth and productivity (grain yield and dry weight accumulation) among the potassium fertilizer treatments was the result of alterations in seasonal nutrient accumulation as plants fertilized with POLY4 and/or POLY4:MOP appeared to be supplied with optimal crop nutrition compared to plants fertilized with MOP and/or those that did not receive potassium fertilizer. These results, in addition to the new discovery of a vast Zechstein deposit potentially keeping product cost low, suggest that polyhalite – in the form of POLY4 – may be an efficient and effective premium fertilizer source for corn growers in central Illinois.

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INTRODUCTION

Modern corn (*Zea mays* L.) hybrids coupled with advanced agronomic practices have led to an increased yield potential of corn (Tollenaar and Lee, 2002). A large component of utilizing corn's full yield potential is better management of crop nutrition (Ruffo et al., 2015). Even though they are typically the easiest to manage, nutrient deficiencies are one of the most common factors limiting corn yield worldwide (Mueller et al., 2012). Corn must be supplied with twelve essential mineral nutrients for optimal growth and productivity, some of which are accumulated in greater amounts than others and thus are considered macronutrients or micronutrients. The six macronutrients needed in the greatest amounts are nitrogen (N), phosphorus (P) potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). The six micronutrients needed in smaller amounts are boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). Although corn can acquire these nutrients from either the soil, atmospheric deposition, or through organic matter mineralization (Halvin et al., 2005), the amount, rate, and duration at which an individual nutrient is supplied by the soil can be limiting (Mueller et al., 2012 and Bender et al., 2013). As a result, commercial fertilizer applications of mineral nutrients are commonly applied to agricultural production systems to support crop nutrient demands that the soil cannot adequately supply.

Polyhalite

Polyhalite is a naturally occurring evaporite mineral that contains 14% K_2O, 10% Ca, 4% Mg, and 19% S, all of which are required for corn production in relatively large quantities. Polyhalite has been proposed as a good fertilizer source for corn production in the United States (Barbarick, 1989; Fraps and Schmidt, 1932), but until recently it has not been widely offered as a commercially available fertilizer due to limited supply, and as a result limited research has been conducted on the agronomic value of using polyhalite as a commercial fertilizer for corn production. Renewed interest in polyhalite as a commercial fertilizer for United States corn production has stemmed from the discovery of a massive Zechstein deposit in the North Sea basin off the cost of the United Kingdom (Kemp et al., 2016). The deposit contains the largest and purest form of polyhalite ever discovered, containing enough of the mineral to support one hundred plus years of fertilizer production for global use (Sirius Minerals, 2016). Sirius Minerals, a company formed to develop and market the new fertilizer, has started to commercially produce a granulated version of polyhalite with the trade name POLY4. The granulated fertilizer, POLY4, has a relatively low salt index compared to other potassium fertilizers such as muriate of potash and sulfate of potash, and thus it is a safer fertilizer to position close to the seed (Barbier et al, 2017). The release of the nutrients contained within POLY4 also tend to be more season-long due to the fertilizer's lower solubility in water (Barbarick, 1991; Jiang et al., 2016). All nutrients contained within POLY4 – potassium, calcium, magnesium, and sulfur – have congruent dissolution and are available for crop uptake (Barbier et al., 2017).

Potassium

One of the first nutrients recognized in polyhalite was potassium. Potassium is one of the most abundantly needed plant nutrients, and it is the main cation by mass in plant tissue (Nieves-Cordones et al., 2016). The widely used nutrient has several major functions in the plant: synthesis of proteins and starch, activation of enzymes for adenosine triphosphate (ATP) production, and most importantly the regulation of water within the plant (IPNI, 2006a). Potassium's role in osmoregulation plays a key role in the opening and closing of stomata (Ebrahimi et al., 2011), and as a mechanism of tolerating drought conditions (Aslam et al., 2013). In addition, plants that have an adequate level of potassium in their cells have an increased ability to withstand the effects of disease damage, frost, and insect damage (Johnston 2003).

The most commonly applied potassium fertilizer in the United States for corn production is potassium chloride (0-0-60-45Cl) (IPNI, 2010). Potassium chloride, also referred to as muriate of potash (MOP), is the most widely used potassium fertilizer due to its relatively low cost and high potassium concentration compared to other K fertilizer sources (IPNI, 2010). Although less common, other potassium fertilizers applied to corn are sulfate of potash (0-0-50-17S), potassium magnesium sulfate (0-0-22-11Mg-22S), and potassium thiosulfate (0-0-25-17S) (IPNI, 2006a). The decision to apply potassium fertilizer is commonly based on two fertilization methods known as the sufficiency approach and the maintenance approach (Bray, 1944). The sufficiency approach relies solely on soil test levels and target yield goals to determine if fertilizer applications should be made (Olson, et al., 1987). One issue that arises with this approach is the variability that is associated with various soil K tests. Current soil K tests procedures are not calibrated for many soils in the northern US corn growing states and require plot validation to determine if a yield response is likely to occur from potassium fertilization (Khan et al., 2014). Independent of potassium fertilizer applications, soil test K levels can increase and decrease based on the time of year the soil sample was taken (Liebhardt and Teel, 1977). As a result of this variability, some growers have resorted to the maintenance approach. The maintenance fertilizer application concept recommends that fertilizer applications be made each year to offset the nutrient removal that occurs with harvest in order to maintain soil fertility levels (Vitosh et al., 1995). This approach has been challenged in United States corn growing states such as Illinois because the soils in these geographical regions have massive reserves of mineral and non-exchangeable K, which can resupply the fraction of potassium that is available for crop uptake (Stewart, 1987; Bray and

DeTurk, 1938). How fast the resupply of potassium to the plant available fraction takes place is strongly dependent on the type of clay minerals present and can be quite slow for some minerals (Attoe, 1946; Stewart, 1987). Although potassium may be present in the soil in adequate amounts, the rate at which potassium is available for crop uptake might be temporally limited because of the large quantities accumulated during vegetative growth with over two thirds of the total uptake occurring before flowering (Bender et al., 2013).

Calcium, Magnesium, and Sulfur

Two nutrients that are also contained in polyhalite but that are less commonly fertilized in the northern United States corn growing states are calcium and magnesium (Fernandez and Hoeft, 2009). Calcium is used by plants for cell wall structure and membrane integrity. The divalent nutrient also plays a part in cell elongation, enzymatic processes, and uptake of other nutrients (IPNI, 2006b). Calcium has been linked to disease resistance in plants due to its role in cell wall strength and intracellular signaling (Easterwood, 2012). Typically, soils throughout northern US corn growing states supply enough exchangeable calcium (300-5000 ppm) for adequate corn production (Kelling and Schulte, 1998). However, additional fertilization of calcium has shown to have beneficial effects on corn leaf senescence, plant growth regulator activities, and nutrient mobility within the plant (Poovaiah and Leopold, 1973).

Magnesium serves a role in the synthesis of proteins and ATP, and it is needed for transport of carbohydrates. Magnesium is also the central atom of the chlorophyll molecule, and as such is essential for photosynthesis (IPNI, 2006c). Similar to calcium, magnesium is associated with disease resistance in plants (Huber and Jones, 2013), and can enhance nitrogen uptake (Potarzycki 2010; Szulc 2010). Most agronomic fertilizer recommendations, however, do not currently advise the application of magnesium for Illinois corn production because soils in this state generally have sufficient levels for optimal productivity (Fernández and Hoeft, 2009).

The final nutrient found in polyhalite is sulfur. Sulfur is a key component of the amino acids cysteine and methionine, making it essential for protein synthesis in plants (Jeschke et al., 2010). Sulfur is also needed for chlorophyll production and seed formation (IPNI, 2006d). In Midwest soils, upwards of 98% of the total sulfur contained in the soil profile is found in the soil organic matter (Tabatabai and Bremner, 1972). Sulfur is predominately supplied to the crop via microbial decomposition of organic matter (i.e. mineralization), and can be taken up by plants or leached out of the soil profile with water (Fernández et al., 2012). In the past, sulfur fertilization has typically not been recommended for the majority of Midwest soils, due to a combination of generally high organic matter, atmospheric deposition of S, and manure applications. However, in recent years, the probability of getting an economically favorable yield-response to sulfur fertilization has been increased in the Midwest for a number of reasons (Sawyer et al., 2011). Since the implementation of the Clean Air Act in 1970, atmospheric deposition of sulfur has significantly decreased over the majority of the United States. (Jeschke et al., 2010). Manure applications in Illinois have also steadily decreased in recent years to a current level of only 600,000 acres (<5%) of the total production land (USDA-NASS, 2012). In addition to decreased atmospheric deposition and manure applications, current agronomic production systems that use nitrogen fertilizers at rates beyond crop removal have the potential to decrease soil organic matter over time (Khan et al., 2007). As a result, sulfur fertilization may become increasingly more important as higher grain yields are achieved each year.

Balanced Nutrition

Balanced crop nutrition, is the concept of providing all the essential plant nutrients needed for optimized crop production. Balanced fertility can have significant effects on plant resistance to disease, grain quality, nutrient uptake, crop yield, and overall crop growth and development (Fageria, 2001; Huber and Jones, 2013; Jakobsen, 1993; Yang et al., 2004). Balanced fertility in plants is crucial due to the various interactions that occur between nutrients (Dibb and Thompson, 1985; IPNI, 1998; Usherwood, 1994), which can either be synergistic or antagonistic (Fageria, 2001). Application of a single nutrient, like potassium, can cause antagonistic effects on the uptake of calcium and magnesium (Jakobsen, 1993; Pathak and Kalra, 1971). Regardless, the most widely used potassium fertilizer in US corn production is muriate of potash (MOP), which only supplies one essential macronutrient needed for corn production (IPNI, 2010). The negative effects of fertilizing with a solo macronutrient, as in the case of MOP, have been documented in a large survey of yield response trials where MOP did not increase crop yield (Khan et al., 2014). Fertilization with polyhalite on the other hand, could potentially supply corn with a balanced mixture of potassium, calcium, magnesium, and sulfur without the negative effects of chlorine and overloading the soil and plant with a single nutrient (Barbarick, 1991; Vale, 2016; Yermiyahu et al., 2017).

Therefore, when comparing potassium fertilization with MOP and polyhalite fertilizers, synchrony of nutrient release for crop uptake, and the extent to which K, Mg, Ca, and S affect nutrient availability in the soil could be important. Because Ca and Mg compete with K on cation exchange sites, and since sulfur fertilization is becoming more common in U.S. corn production, polyhalite may have potential to be used as both a potassium and a sulfur fertilizer. Although a recent study by Bender et al. (2013) documented seasonal patterns of nutrient accumulation and partitioning of modern corn hybrids, there is limited data on the change in pattern of uptake, partitioning, and remobilization of nutrients released from different potassium fertilizers such as MOP and polyhalite. The objective of this study was to quantify the effects of polyhalite fertilizer – in the form of POLY4 – compared to MOP on increasing corn productivity as a result of individual versus multinutrient fertilization.

MATERIALS AND METHODS

Experimental Design

The experiment was conducted over the years of 2017 and 2018. Treatments were arranged in a randomized complete block experimental design with six replications. Three potassium fertilization strategies were compared, using two fertilizer products: muriate of potash (MOP; 0-0-60) and polyhalite (POLY4; 0-0-14-17Ca-6Mg-19S) as 100% MOP, 100% POLY4, and a blend of 75%POLY4:25%MOP (Table 1). All fertilizer treatments were applied to obtain 75 lb acre^{-1} of potassium (K_2O), but no additional nutrients were applied to balance for calcium, magnesium, and sulfur. An individual experimental unit (plot) consisted of eight rows, 11.4 m (37.4 ft.) in length with 0.76 m (30 in.) spacing. Rows two and three were used for plant sampling, and rows six and seven were used to collect yield data.

Field Characteristics

The trial was conducted at the Crop Sciences Research and Education Center in Urbana, IL. Both field sites from 2017 and 2018 were level (0-2% slope) and classified as Elburn silt loam and Flanagan silt loam respectively (Web Soil Survey). Soybean was the previous crop for both site-years. A composite soil sample of each site-year was taken from 0-6 inch depth before planting and analyzed by A & L Great Lakes Laboratories, Inc (Fort Wayne, IN) for organic matter, cation exchange capacity, pH, P, K, Ca, Mg, S, Zn, Mn, B, Fe, and Cu using Mehlich 3 (Table 2).

Agronomic Management

Soil preparation consisted of a fall chisel plow pass followed by two field cultivations in the spring. A base nitrogen rate of 180 lb acre^{-1} was applied preplant incorporated as liquid urea ammonium nitrate (28-0-0). Fertilizer treatments were applied prior to planting and lightly incorporated with a harrow. A commercially available hybrid (DKC64-34 SSRIB; 114-day relative maturity) was planted using a SeedPro 360 planter (ALMACO, Nevada, IA) to achieve an approximate final stand of 34,000 plants acre^{-1}. Fields were planted on April 18th, 2017 and May 14th, 2018. All plots received an in-furrow application of Force 3G (AMVAC, Los Angeles, Ca) [tefluthrin:(2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1α,3α)-(Z)-(±)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate] soil insecticide at planting at a rate of 0.24 lb acre^{-1}.

Both 2017 and 2018 fields were maintained weed-free with a two-pass herbicide program. In 2017 pre-emergence weed control was obtained with an application of 0.63 gal acre^{-1} of Bicep II Magnum (Syngenta, Greensboro, NC) [S-metolachlor: (2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] + atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine). Post emergence weed control was obtained with an application of 0.75 oz acre^{-1} of Armezon (BASF, North Carolina, US) [topramezone: [3-(4,5-dihydro-isoxazolyl)-2-methyl-4 (methylsulfonyl)phenyl](5-hydroxy-1-methyl-1H-pyrazol-4-yl)methanone], 1 lb acre^{-1} of AAtrex Nine-O (Syngenta, Basel, Switzerland) [atrazine: 2-chloro-4-ethylamino-6-isopropylamino-s-triazine], 0.25 gal acre^{-1} glyphosate (N-(phosphonomethyl) glycine in the form of potassium salt as Roundup POWERMAX (Monsanto, St. Louis, MO), and 0.20 gal acre^{-1} of ammonium sulfate. In 2018, pre-emergence weed control was obtained with an application of 0.32 gal acre^{-1} of Verdict (BASF Corporation, Research Triangle Park, NC) saflufenacil [N'-[2-chloro-4-fluror-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide] + dimethenamid-P [(S)-(2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamid)] and 0.37 gal acre^{-1} of Infantry 4L (atrazine; Growmark Bloomington, Illinois). Post emergence weed control was obtained with an application of 0.75 oz acre^{-1} of Armezon, 1 lb acre^{-1} of AAtrex Nine-O, 0.25 gal acre^{-1} Roundup POWERMAX, and 0.20 gal acre^{-1} of ammonium sulfate.

Plant Sampling and Partitioning

To evaluate seasonal dry weight and nutrient accumulation, six plants were sampled at each of six incrementally spaced growth stages: V6 (vegetative leaf stage 6), V10 (vegetative leaf stage 10), V14 (vegetative leaf stage 14), R2 (reproductive blister), R4 (reproductive dough), and R6 (physiological maturity) (Hanway, 1963; Bender et al., 2013). The corresponding growing degree day accumulation for each growth stage was calculated using a base of 50 °F (Table 3). Plants were sampled at the soil surface from rows 2 and 3. Each plant was separated into leaves (leaf blades and leaf sheaths), stalk, reproductive organs (tassel, cob, and husk leaves), and grain tissues, and are referred to as leaf, stalk, reproductive, and grain tissues respectively.

Sample Preparation and Analysis

Tissue samples were dried (167°F) to a constant weight to determine total dry weight. Prior to grinding, leaf and stalk tissue samples from growth stages V14 through R6 were shredded (Vermeer BC600XL Chipper, Vermeer Corporation, Pella, IA) to obtain a representative subsample. Leaf, stalk, reproductive, and grain tissues were ground using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) through a 2 mm mesh screen. Grain dry weight accumulation at R4 was determined from hand-sampled plants, while R6 grain dry weight accumulation was calculated using combine-harvested grain. Grain tissue from plants at the R4 and R6 growth stages was dried to a constant weight, and % moisture content (% MC) was determined using a dielectric (capacitance) type grain moisture meter (SL95, Steinlite Corp., Atchison, KS).

All tissue samples were analyzed for N, P, K, Ca, Mg, and S (A & L Great Lakes Laboratories, Inc, Fort Wayne, IN). Nitrogen was analyzed using a combustion method, and other nutrients were analyzed using a two-part process of acid-microwave digestion followed by Inductively Coupled Plasma (ICP) Spectrometry (Latimer and Horwitz, 2011). Tissue nutrient concentrations for all plant parts are expressed on a dry weight basis. Concentration of nitrogen and phosphorus can be found in the appendix.

Nutrient Uptake

Tissue nutrient concentrations and dry weights were used to algebraically derive nutrient content for each individual plant part. The individual plant part nutrient accumulation was calculated on a per acre basis by multiplying the dry weight and nutrient concentration. Whole plant nutrient uptake was calculated by adding leaf, stalk, reproductive, and grain nutrient contents. Phosphorus and potassium nutrient uptake were converted to P_2O_5 and K_2O using the conversion factors of 2.29 and 1.20, respectively.

Grain Yield, Harvest Index, Yield Components, and Grain Quality

Prior to harvest, stand counts were tallied each year to assess plot-to-plot uniformity throughout the trial, and to record any environmental impacts that may have affected final stand. Harvests were completed on September 23rd, 2017 and September 29th 2018. Rows six and seven of each plot were mechanically harvested with an ALMACO SPC40 combine (ALMACO, Nevada, IA) for determination of grain yield and harvest moisture, and the yield was subsequently standardized to bushels acre^{-1} at 15.5% moisture. Harvest index represents the proportion of whole plant dry weight that is distributed into grain production (Equation 1).

$$Harvest\ Index = \frac{Grain\ Dry\ Weight}{Whole\ Plant\ Dry\ Weight}\ X\ 100 \qquad (1)$$

Subsamples of the grain were collected at harvest and analyzed for yield components (average individual kernel weight and kernel number), and for grain quality (protein, oil, and starch concentrations). Average individual kernel weight was calculated using a subsample of 300 kernels, while kernel number was calculated by dividing the total plot grain weight by the average individual kernel weight. Average individual kernel weight is presented at 0% moisture. Grain quality was analyzed by near-infrared transmittance spectroscopy using an Infratec 1241 grain analyzer (Foss, Eden Prairie, WI) and is presented at 0% moisture.

Statistical Analyses

Data analysis for all results was conducted using PROC MIXED (SAS 9.4; SAS Institute Inc., Cary, NC) with the assumption of equal variances. PROC UNIVARIATE was used to determine potential outliers and assess normality of residuals. Treatment was designated as a fixed effect, and year and replication were assigned as random effects because they were statistically insignificant. Replication was nested within year.

Nutrient uptake and partitioning figures were developed using SigmaPlot (SigmaPlot v14.0; Systat Software Inc., San Jose, CA). Nutrient uptake averages acquired from the statistical analysis and the accumulation of growing degree days per growth stage were imported into SigmaPlot. Seasonal uptake figures were generated with the Simple Spline Curve option using smoothed data points.

RESULTS AND DISCUSSION

Weather Conditions

In central Illinois, the 2017 crop experienced below-average rainfall paired with slightly above average seasonal temperatures (Table 4). The rainfall distribution for 2017 was heavily skewed to the early portion of the growing season. Total precipitation for the 2018 crop growing season (~26 inches) was slightly above average. However, July and April 2017 had below-average precipitation while June and September experienced well-above average precipitation. The 2018 seasonal temperatures in central Illinois were below normal early in the growing season but tended to be at or above normal for the remainder of the season. In both years, weather conditions surrounding pollination were relatively hot and dry (data not shown).

Grain Yield and Harvest Index

The two-year average grain yield for corn that was fertilized with only 180 lb acre^{-1} of nitrogen (untreated control; UTC) was 254 bu acre^{-1}. When averaged across the 2017 and 2018 growing seasons, grain yield was significantly affected by fertilizer treatment applications (Table 5). The average yield for corn fertilized with MOP was similar to corn that did not receive any potassium fertilizer (Table 6), in agreement with results of Khan et al. (2014) that potassium chloride is unlikely to increase crop yield. However, corn that was fertilized with either POLY4 or a blend of POLY4:MOP yielded 6 bu acre^{-1} more than corn that was fertilized with MOP and produced 7 bu acre^{-1} more than corn that did not receive any potassium fertilizer. Interestingly, all three potassium fertilizer applications decreased the dry weight harvest index (Table 6). Typically, management factors that result in an increase in grain yield, such as additional nitrogen fertilizer applications, usually do not lower the harvest index of the crop (Shapiro and Wortmann, 2006), as an increase in grain yield is usually matched by a proportional increase in vegetative biomass. For the MOP treatment, there was a significant decrease in the harvest index compared to the control due to an increase in vegetative biomass without changing the grain production. Uniquely, the increases in grain yield that occurred by fertilizing with POLY4 or POLY4:MOP also resulted in decreases in harvest index (Table 6). Therefore, the significant increase in grain yield as a result of POLY4 and POLY4:MOP fertilization was matched by a proportionally greater increase in vegetative biomass. The increases in both grain yield and vegetative biomass suggest that corn fertilized with POLY4 and POLY4:MOP tended to have an overall better growing environment.

Yield Components and Grain Quality

Yield components were measured to determine how differences in grain yield were achieved and which yield components were most affected by the fertilization treatments. An increase in kernel number generally signifies better growing conditions earlier in the season since the potential kernel number (rows of kernels per ear and kernels per row) is being determined in the vegetative growth stages of crop growth (Abendroth et al., 2011; Andrade et al., 1999). Similarly, kernel weight is usually most affected by late-season growing conditions as this is when grain filling occurs (Maddonni, et al., 1998). An exception to these general yield component effects is when one yield component increases or decreases the other yield component in what is known as yield component compensation (Haag et al., 2017). Yield component compensation can be alluded to in the MOP-induced effects on the resulting changes in corn kernel number and kernel weight, as MOP-fertilized plants had slightly fewer kernels, and as a result, the kernels tended to be heavier (Table 6). Similarly, corn fertilized with just POLY4 tended to have heavier kernels but without an increase in kernel number. The increase in yield as a result of kernel weight may be explained by the fact that POLY4 acts as a slow-release fertilizer due to its relatively low solubility compared to other potassium fertilizers (Barbarick, 1991). When corn was fertilized with the two sources blended together, both kernel weight and kernel number tended to increase. Additionally, plants fertilized with any of the three potassium fertilizer treatments had significant increases in concentrations of grain oil and protein (Table 6). Corn fertilized with POLY4 and/or POLY4:MOP not only had higher levels of grain oil and protein but also higher grain yields.

Dry Weight Accumulation

Total aboveground dry weight accumulation was documented at six growth stages throughout the entire growing season (Table 3). Seasonal dry weight accumulation was linear from V10 to R6 with a preceding lag phase from emergence to V10 (Figure 1). The effect of the potassium treatments on whole plant biomass accumulation primarily occurred during reproductive growth, and at physiological maturity all three potassium fertilizer treatment applications increased whole plant biomass (Tables 7 and 8). Increased potassium uptake as a result of potassium fertilization has previously been shown to increase dry stover biomass in corn (Heckman and Kamprath, 1992). Results from the current study show that corn fertilized with only POLY4 had significantly greater whole plant biomass accumulation compared to corn fertilized with MOP through all of the reproductive growth stages. Furthermore, compared to plants fertilized with only MOP, those fertilized with either POLY4 or POLY4:MOP tended to have greater whole plant biomass at all sampled growth stages (Table 8, Figure 1).

The most prominent difference in biomass partitioning due to the fertilizer treatments was in the amount partitioned to stalk material (Figure 1, Table 8), and potassium fertilization is known to have a positive impact on stalk strength and resistance to lodging (Liebhardt and Murdock, 1965; Welch and Flannery, 1985; Xu et al., 2018). From growth stages R2 to R6, all three potassium fertilizer applications significantly increased stalk biomass compared to the untreated control which did not receive any potassium fertilizer (Table 8). In addition to an increase in stalk biomass accumulation late in the growing season, all three potassium fertilizer applications resulted in a greater retention of leaf biomass at the R6 growth stage. Adequate potassium nutrition is crucial for leaf development and proper leaf elongation (Jordan-Mellie and Pellerin, 2004). Corn fertilized with either POLY4 or POLY4:MOP had greater amounts of dry weight partitioned into grain tissues at R6 compared to corn that was fertilized with MOP or that was not fertilized at all. Generally, corn fertilized with potassium resulted in greater overall plant dry weight accumulation.

Leaf Nutrient Concentrations

The nutrient status of corn can be assessed using the process of tissue sampling. Corn leaves are commonly sampled throughout the growing season and sent into commercial laboratories where the leaf samples are analyzed for mineral nutrient concentrations (Mills and Jones, 1996). Typically, corn leaf samples are taken from the uppermost collared leaf during the vegetative growth stages and from the ear leaf during the reproductive growth stages (Binford et al., 1990). Although tissue samples from this study included leaf material from the entire plant, nutrient concentrations were significantly affected by fertilizer treatments (Table 9). Differences in leaf potassium concentration were more prominent from the R2 growth stage onward (Table 10). Fertilization of corn with MOP resulted in higher leaf potassium concentrations compared to the control at all reproductive growth stages. Furthermore, corn fertilized with either the POLY4 or POLY4:MOP treatments had even higher potassium concentrations in leaf material compared to corn that was fertilized with only MOP. Differences in leaf potassium concentration among the three potassium fertilizer treatments and the unfertilized control became ever more apparent later in the season.

Increased potassium leaf concentrations as a result of potassium fertilizer treatments, especially in the case of POLY4 and POLY4:MOP fertilizer treatments, did not appear to have a negative effect on calcium concentrations in leaf material for the majority of the growing season (Table 11). An increase in plant potassium concentration can lead to antagonism with calcium and magnesium. Antagonism between plant nutrients is a situation where the presence of one nutrient decreases plant accumulation of another nutrient (Jakobsen, 1993; Pathak and Kalra, 1971). The supplemental calcium supplied by POLY4 and POLY4:MOP, 54 and 40 pounds acre^{-1} of calcium, respectively, may have counter-acted the calcium-based antagonistic effects of increased plant potassium. Corn leaf calcium concentrations were not significantly affected by fertilizer treatments for the majority of the crop growing season, even when calcium was supplied via POLY4 and POLY4:MOP fertilization (Table 9). In some cases, an application of a nutrient or fertilizer does not have an effect on the concentration of nutrients within the crop due to a phenomenon known as growth dilution; which is when nutrient concentrations are decreased as a result of increased crop biomass accumulation (Terman and Allen, 1974; Terman et al., 1977). Calcium concentrations in corn leaf material remained steady throughout the majority of the growing season even in the presence of increased vegetative biomass and potassium concentrations. These results suggest that fertilization with POLY4 and POLY4:MOP may be used to help supply adequate potassium to corn without the antagonistic effects on calcium uptake.

Although sampling methods for corn leaf tissue differed from that of standard tissue sampling procedures, leaf magnesium concentrations of corn that did not receive any potassium fertilizer (UTC) were markedly high compared to the recommended levels for corn production in the Northern U.S. Corn Belt of 0.16-0.40 (Kelling et al., 2000) (Table 10). The higher leaf magnesium concentrations in corn that was not fertilized with potassium can be explained by the average soil test levels for potassium, calcium, and magnesium (Table 2). In addition to relatively high magnesium soil test levels, the base saturation of magnesium was high compared to the base saturation of potassium; which can lead to limited K uptake and excessive Mg uptake (McLean, et al., 1983). In regard to the current study's potassium fertilizer applications, leaf magnesium concentrations decreased as the concentration of potassium in the leaf increased. A significant decrease in leaf magnesium concentration as a result of K fertilization was detected at four of the six sampled growth stages; the antagonism between potassium and magnesium was most prevalent at the R4 growth stage (Table 10). Decreases in leaf magnesium concentration occurred even in plants that were fertilized with POLY4 and POLY4:MOP, which supplied supplemental magnesium at 21 and 16 pounds acre^{-1}, respectively. Fertilization with only MOP did not consistently decrease corn leaf magnesium concentration compared to POLY4 and POLY4:MOP fertilization; likely due to the fact that corn fertilized with MOP had less K concentration in the leaf material compared to corn fertilized with POLY4 and POLY4:MOP. Overall, potassium and magnesium antagonism was evident as increased leaf potassium concentrations tended to decrease leaf magnesium concentrations, especially in the case of POLY4 and POLY4:MOP fertilization (Table 10). The antagonism of magnesium due to potassium fertilization may not be a negative side effect in this circumstance since plants that did not receive any potassium fertilizer had relatively high magnesium concentrations to begin with.

The effect of fertilizer treatment on corn leaf sulfur concentrations was highly significant at all of the sampled growth stages (Table 9). The concentration of sulfur in corn leaf material steadily decreased as the growing season progressed (Table 10). Although leaf sulfur concentrations decreased overall as the season progressed, at all six of the sampled growth stages, corn fertilized with POLY4 and POLY4:MOP had greater leaf sulfur concentrations compared to corn fertilized with MOP or unfertilized. Corn fertilized with MOP had similar leaf sulfur levels to the unfertilized control plants throughout the growing season. The magnitude of increase in leaf sulfur concentration for corn fertilized with POLY4 and POLY4:MOP did not appear to be skewed to certain portions of the growing season, suggesting that the crop was supplied with adequate sulfur throughout the season (Table 10).

Nutrient Uptake and Partitioning

A common source of misunderstanding in crop nutrition and nutrient uptake research stems from confusion around the difference between nutrient concentrations and total nutrient content/accumulation. Nutrient concentration, as described in the leaf nutrient concentration section, is the amount of an element/nutrient per unit dry weight (percent, ppm). On the other hand, nutrient content or nutrient accumulation is the total amount of an element/nutrient measured on a per-plant or plant-part basis; this value is dependent upon the concentration and total dry weight biomass (Bauer et al., 1997). Nutrient uptake is the commonly used term when nutrient content or accumulation is expressed on an area basis such is the case with “lbs of nutrient per acre”. The advantage of displaying nutrient uptake on a content basis stems from the fact that when a nutrient is deficient or limiting, fertilization of the lacking nutrient may result in an increase in crop biomass. The increase in crop biomass from fertilization results in an overall greater uptake of the lacking nutrient, yet the nutrient concentration may remain the same due to a dilution effect (Burns, 1992). If nutrient uptake is significantly higher, an increase in crop biomass will be accompanied by a concomitant increase in nutrient concentration as well.

Potassium Nutrient Uptake and Partitioning

Differences in whole plant potassium uptake, as a result of the different potassium fertilizer treatments, became more prevalent later in the growing season (Table 11). This result can be explained by the nutrient release characteristics of the two different potassium sources. The solubility (20°C) of MOP is 344 g/L (IPNI, 2010) which leads to a more quick release of nutrients into soil solution. POLY4, on the other hand, has a lower solubility (25 °C) of 27 g/L (Sirius Minerals, 2016), which leads to a more season-long, slow release of the nutrients contained within the granule (Barbarick, 1991). Potassium, due to its unique ionic size, is prone to fixation within 2:1 clay minerals in the presence of repeated wetting and drying cycles (Attoe, 1946; Khan et al., 2014). In the case of clay minerals such as illite, a very abundant clay mineral in Illinois (Freiburg et al., 2016), potassium that becomes fixed between clay layers is less available for plant uptake due to its relatively slow conversion from fixed forms to exchangeable forms (Stewart, 1987). Compared to a slow release fertilizer source such as POLY4, potassium supplied by a quick release fertilizer source such as MOP would have less opportunity for plant uptake due to the fact that the fertilized potassium ions would be present in the soil environment longer and thus more susceptible to potassium fixation.

In the present study, plants fertilized with MOP resulted in greater whole plant potassium uptake compared to those that did not receive any potassium fertilizer (UTC); yet still, plants fertilized with POLY4 and POLY4:MOP had significantly greater potassium uptake compared to those fertilized with only MOP (Table 12, Figure 2). Remobilization of leaf potassium into the grain and reproductive tissues started at R2 and was most pronounced in corn that did not receive potassium fertilizer (Figure 2). Potassium was partitioned to leaf material more than any other plant part, and potassium accumulation into corn leaf material was greatest for corn fertilized with POLY4 and POLY4:MOP (Table 12). Total potassium accumulation into stalk material, and reproductive organs also tended to be greatest in corn fertilized with POLY4 and POLY4:MOP. Conversely, the amount of potassium in the grain was not significantly affected by any of the fertilizer treatments, similar to potassium partitioning patterns that have been reported in other corn nutrient uptake research (Bender et al., 2013; Karlen et al., 1988). Overall, fertilization of plants with POLY4 and POLY4:MOP resulted in greater potassium uptake compared to fertilization with MOP or to plants that were not fertilized with potassium.

Calcium, Magnesium, and Sulfur Nutrient Uptake and Partitioning

Whole plant calcium nutrient accumulation was not significantly affected by potassium fertilizer treatments for the majority of the growing season (Table 11). However, calcium partitioning throughout the plant, specifically in stalk material, was significantly affected by fertilizer treatment at four of the six sampled growth stages (Table 13). Plants fertilized with any of the three potassium treatments had significantly greater calcium accumulated into stalk material compared to those that did not receive potassium fertilizer (Table 13). The increase in calcium being partitioned to stalk material was most likely due to the greater accumulation of stalk dry weight in plants fertilized with potassium (Table 8). The direct correlation of stalk biomass accumulation and stalk calcium accumulation is likely because calcium has a key role in cell structure and membrane integrity. Calcium provides cell wall strength and rigidity by forming cross-links within the pectin polysaccharide matrix, and in the presence of rapid plant growth, stem strength is strongly affected by calcium availability (Easterwood, 2012). Similar to results discussed in Bender et al. (2013) and Karlen et al. (1988), calcium translocation to grain tissue was negligible, and thus grain calcium accumulation was excluded from these results (Table 13). Although calcium partitioning to stalk material had the most significant changes brought on by fertilization treatments, the majority of the plant's calcium accumulation was partitioned to leaf material (Figure 3). In general, potassium fertilizer treatments tended to increase whole plant calcium uptake mostly because of the underlying increases in stalk and total aboveground biomass

(Table 8 and 13). However, in the current study plants accumulated greater calcium in stalk material even when they were not fertilized with a calcium containing fertilizer.

Total magnesium uptake differences as affected by potassium fertilizer treatments were most prominent at the R2 and R4 sampled growth stages (Table 11). The fertilizer treatment differences causing whole plant magnesium uptake variations were predominately the result of changes in the amount of magnesium partitioned to leaf material (Table 14). Compared to plants that were fertilized with only MOP or those that did not receive potassium fertilizer, fertilization with only POLY4 decreased both leaf and whole plant magnesium accumulations at the R2 and R4 growth stages. However, plants fertilized with POLY4:MOP decreased leaf and whole plant magnesium contents only at the R4 growth stage. At physiological maturity, leaf and whole plant accumulations of magnesium in corn were similar, regardless of treatment. Although leaf magnesium concentrations were significantly less than the control in plants fertilized with POLY4 and POLY4:MOP at R6 (Table 10), the corresponding increase in aboveground biomass resulted in the overall uptake of magnesium among plants fertilized with different potassium sources to be relatively similar (Table 14). Seasonal uptake, partitioning, and remobilization of magnesium was similar for plants fertilized with only MOP and those that did not receive any potassium fertilizer (Figure 4). Conversely, plants fertilized with POLY4 and those fertilized with POLY4:MOP had uniquely different magnesium uptake patterns which were predominately driven by differences in leaf magnesium accumulation and partitioning. Leaf magnesium accumulation was different for plants fertilized with POLY4 and POLY4:MOP not only due to the fact that there were differences in the timing of peak magnesium accumulation, but also because leaf magnesium in plants that were fertilized with POLY4 and POLY4:MOP did not appear to remobilize to other areas of the crop as was the case with unfertilized plants and those fertilized with MOP. Similar to potassium uptake, fertilization treatments did not have a significant effect on the accumulation of grain magnesium (Table 14).

Sulfur accumulation was significantly affected by fertilizer treatment for every plant part at every growth stage except stalk material at V6 (Table 11). Fertilization with POLY4 and POLY4:MOP resulted in significantly greater whole plant sulfur uptake compared to plants fertilized with MOP and those that did not receive potassium fertilizer (Table 15). Plants fertilized with POLY4 and POLY4:MOP received 102 and 76 lb S acre^{-1} respectively, which is much greater than the estimated sulfur removal rate of 15 lb acre^{-1} for a 250 bu acre^{-1} corn crop (Bender et al., 2013). The higher rates of sulfur applied in the form of POLY4 and POLY4:MOP resulted in greater sulfur accumulation in leaf, stalk, reproductive, and grain tissues for the majority of the growing season (Table 15). Plants fertilized with MOP did not receive any additional sulfur from fertilizer, yet they had greater total sulfur uptake compared to those that did not receive any fertilizer. The increase in total plant sulfur accumulation when fertilized with MOP was predominately due to the increased total aboveground biomass that resulted from the potassium fertilizer application (Table 8). In the presence of all four treatments, plants partitioned the majority of their total sulfur uptake to leaf and grain tissues, and the pattern of partitioning and remobilization did not appear to be affected by fertilizer treatment (Figure 5). Overall, fertilization with POLY4 and POLY4:MOP provided growing corn plants with adequate season-long sulfur.

Nitrogen and Phosphorus

Nitrogen and phosphorus were analyzed for seasonal accumulation in this study; however these nutrients were not directly applied as fertilizer treatments. Results on leaf nutrient concentration and seasonal accumulation for both nitrogen and phosphorus can be found in the appendix (Tables 16-20). Similarly, patterns of nutrient uptake, partitioning, and remobilization for nitrogen and phosphorus can also be found in the appendix (Figure 6-7).

SUMMARY AND CONCLUSIONS

The two years of research focusing on the seasonal nutrient accumulation of corn as affected by potassium fertilizer treatments generally experienced weather conditions that were conducive for high-yielding corn grain production (Table 4). Our research agrees with that of Khan et al. (2014), in that fertilizing corn with MOP did not significantly increase yield (Table 6). However, corn that was fertilized with either POLY4 or a blend of POLY4:MOP yielded a statistically significant 6 bu acre^{-1} greater than corn fertilized with MOP. Plants that were fertilized with either of the three potassium fertilizer treatments resulted in greater total dry weight accumulation compared to the untreated control, where stalk dry weight increased the most from potassium fertilization, but leaf dry weight also tended to increase (Tables 7 and 8).

Differences in crop growth and productivity (grain yield and biomass accumulation) from fertilizer treatments were the result of differences in seasonal nutrient accumulation (Tables 12–15). Plants fertilized with POLY4 and POLY4:MOP had greater potassium and sulfur uptake compared to the untreated control and to MOP (Tables 12 and 15). Although total potassium uptake was significantly increased by fertilizer treatment, calcium uptake was not affected, suggesting there was no antagonism between potassium and calcium uptake (Table 13). Conversely, in the latter portion of the growing season, total magnesium uptake tended to be negatively correlated to total potassium uptake (Table 14), which may have been due to the soil's magnesium level and base saturation being considerably higher than what is needed for corn production (Table 2). Consequently, the leaf magnesium concentrations in the unfertilized corn were excessively high, and thus the antagonism between potassium and magnesium (increased potassium uptake resulted in decreased magnesium uptake) was considered to be beneficial (Table 10). Increased nutrient uptake as a result of POLY4 fertilization appeared to be due to its multi-nutrient, slow-release delivery which supplied the crop with a balanced mixture of potassium, calcium, magnesium and sulfur throughout the season, resulting in less nutrient fixation and greater availability of these nutrients to the crop.

Although polyhalite has not been widely available as a commercially available fertilizer, results from this study, in addition to the new discovery of a vast Zechstein deposit, suggest that polyhalite – in the form of POLY4 – could be a beneficial premium fertilizer source for corn growers in central Illinois.

TABLES AND FIGURES

Table 1. Potassium fertilizer treatments and their corresponding mineral analyses applied preplant at Champaign, Illinois in 2017 and 2018.

Treatment	K_2O	Ca	Mg	S
	lb acre^{-1}			
UTC	-	-	-	-
MOP	75	-	-	-
POLY4:MOP	75	40	16	76
POLY4	75	54	21	102

Table 2. Average pre-plant soil properties and Mehlich 3-extraction-based mineral test results for the trial fields at Champaign, IL in 2017 and 2018.

OM†	CEC	pH	P	K	Ca	Mg	S	Zn	B	Mn	Fe	Cu	Na
%	meq/100g	units											
4.2	23.3	5.9	22	98	2857	472	8.5	1.3	0.6	31	141	2.2	0.0
Base saturation (%)††		19.0	-	1.2	62.3	17.5	-	-	-	-	-	-	0.0

† OM, organic matter.

†† Base saturation calculated using soil test results of pH, potassium, calcium, magnesium, and sodium.

Table 3. Cumulative growing degree days (Base 50 ºF) at six growth stages for corn grown at Champaign IL in 2017 and 2018.

	Growth Stage					
Year	V6	V10	V14	R2	R4	R6
	GDDs					
2017	552	995	1381	1741	2153	2727
2018	572	1070	1287	1737	2250	3070
2-Year Average	562	1033	1334	1739	2202	2898

Table 4. Precipitation and temperature during the production season at Champaign, IL for 2017 and 2018 compared to the 30-year average.

Month	Precipitation, inch 2017	2018	30-Year Average	Temperature, °F 2017	2018	30-Year Average
April	6.2	2.5	3.6	57	46	52
May	5.6	4.2	4.9	61	72	63
June	2.5	7.3	4.3	73	75	72
July	2.2	3.2	4.7	77	75	75
August	2.2	4.0	3.9	72	75	73
September	0.8	4.7	3.1	69	83	66
Total/Avg.	19.5	25.9	24.5	68	71	67

Table 5. Test of fixed effects for average grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations) due to potassium fertility treatments for corn grown at Champaign IL in 2017 and 2018.

			Yield Components		Grain Quality		
Source of variation	**Yield**	**Harvest Index**	**Kernel Number**	**Kernel Weight**	**Oil**	**Protein**	**Starch**
	P > F						
Treatment	0.0226	0.0820	0.1471	0.1602	0.0023	0.0281	0.0052

Table 6. Average grain yield, harvest index, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations) resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018. Grain yield is presented at 15.5% moisture; kernel weight and grain quality are presented at 0% moisture.

			Yield Components		Grain Quality		
Treatment	**Yield**	**Harvest Index**	**Kernel Number**	**Kernel Weight**	**Oil**	**Protein**	**Starch**
	bu acre^{-1}	%	kernels/m^2	mg/kernel	%		
UTC	254	55.9	4981	272	4.1	7.7	73.1
MOP	255	54.5	4917	276	4.3	7.9	72.6
POLY4:MOP	261	54.1	5060	274	4.3	7.8	72.7
POLY4	261	53.7	4980	278	4.2	7.8	72.8
LSD (α =0.10)	4.7	1.4	104	5	0.1	0.1	0.25

Table 7. Tests of potassium fertility treatment significance for average dry weight accumulation by plant part at six growth stages for corn grown at Champaign IL in 2017 and 2018.

Plant Part	Growth Stage V6	V10	V14	R2	R4	R6
	P > F					
Whole Plant	0.0036	0.1815	0.4418	0.0003	0.0707	0.0003
Leaves	0.1530	0.5565	0.7734	0.9352	0.8908	0.8117
Stalk	0.1763	0.0825	0.5862	0.0002	0.0002	<.0001
Reproductive				0.7173	0.8603	0.4584
Grain					0.1988	0.0979

Table 8. Seasonal dry weight accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

Treatment	Growth Stage V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	356 c†	2497 b	6294 a	10434 b	16904 b	21812 c
MOP	370 b	2458 b	6368 a	10425 b	17098 b	22699 b
POLY4:MOP	391 a	2674 a	6306 a	11233 a	17273 ab	23275 ab
POLY4	387 ab	2591 ab	6560 a	11381 a	17953 a	23292 a
	Leaves					
UTC	301 c	1746 a	4084 a	4234 b	4266 b	3475 b
MOP	315 bc	1714 a	4192 a	4247 b	4408 ab	3773 a
POLY4:MOP	332 a	1842 a	4115 a	4471 a	4388 ab	3794 a
POLY4	325 ab	1807 a	4251 a	4490 a	4500 a	3837 a
	Stalk					
UTC	55 b	751 b	2210 a	3679 c	3697 b	3311 b
MOP	55 b	744 b	2176 a	3914 b	4059 a	3728 a
POLY4:MOP	59 ab	832 a	2191 a	4056 ab	4078 a	3769 a
POLY4	62 a	784 ab	2309 a	4107 a	4226 a	3765 a
	Reproductive					
UTC	-	-	-	2521 b	3046 ab	2324 b
MOP	-	-	-	2264 c	2905 c	2421 ab
POLY4:MOP	-	-	-	2706 ab	2960 bc	2414 ab
POLY4	-	-	-	2784 a	3098 a	2521 a
	Grain					
UTC	-	-	-	-	5895 ab	12702 b
MOP	-	-	-	-	5726 b	12777 b
POLY4:MOP	-	-	-	-	5847 ab	13298 a
POLY4	-	-	-	-	6129 a	13169 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 9. Tests of potassium fertility treatment significance for average leaf nutrient concentration of potassium, calcium, magnesium, and sulfur at six growth stages for corn grown at Champaign IL in 2017 and 2018.

	Growth Stage					
Nutrient	V6	V10	V14	R2	R4	R6
	P > F					
Potassium	0.0582	0.0966	0.0360	<.0001	0.0001	<.0001
Calcium	0.4412	0.3584	0.9254	0.0517	0.9805	0.5894
Magnesium	0.0657	0.0162	0.3035	0.0013	<.0001	0.2005
Sulfur	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Table 10. Seasonal leaf nutrient concentrations for potassium, calcium, magnesium, and sulfur resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	%					
	Potassium					
UTC	2.19 b†	1.44 b	1.38 b	1.28 c	1.18 c	0.54 c
MOP	2.37 a	1.52 ab	1.40 b	1.41 b	1.31 b	0.71 b
POLY4:MOP	2.41 a	1.44 b	1.44 b	1.53 a	1.43 a	0.87 a
POLY4	2.38 a	1.59 a	1.54 a	1.52 a	1.40 a	0.81 a
	Calcium					
UTC	0.74 a	0.54 a	0.54 a	0.67 a	0.76 a	0.96 a
MOP	0.77 a	0.55 a	0.55 a	0.66 a	0.77 a	0.93 a
POLY4:MOP	0.77 a	0.52 a	0.54 a	0.67 a	0.77 a	0.93 a
POLY4	0.75 a	0.51 a	0.54 a	0.61 b	0.77 a	0.94 a
	Magnesium					
UTC	0.54 a	0.58 a	0.52 ab	0.57 a	0.68 a	0.67 a
MOP	0.50 b	0.56 a	0.53 a	0.56 a	0.63 b	0.65 ab
POLY4:MOP	0.48 b	0.51 b	0.51 ab	0.55 a	0.51 c	0.63 b
POLY4	0.49 b	0.51 b	0.48 b	0.45 b	0.53 c	0.62 b
	Sulfur					
UTC	0.30 b	0.23 b	0.18 b	0.16 b	0.15 b	0.12 b
MOP	0.30 b	0.22 b	0.17 b	0.16 b	0.16 b	0.13 b
POLY4:MOP	0.33 a	0.26 a	0.21 a	0.19 a	0.18 a	0.16 a
POLY4	0.33 a	0.26 a	0.22 a	0.19 a	0.19 a	0.16 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 11. Tests of potassium fertility treatment significance for average nutrient accumulations of potassium, calcium, magnesium, and sulfur by plant part at six growth stages for corn grown at Champaign IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
			P > F			
			Potassium			
Whole Plant	0.0002	0.1495	0.0024	<.0001	<.0001	<.0001
Leaves	0.0116	0.2016	0.0898	<.0001	0.0001	<.0001
Stalk	0.0566	0.1746	0.2578	0.0197	0.0004	0.0001
Reproductive				0.0004	0.0333	0.2728
Grain					0.3618	0.7492
			Calcium			
Whole Plant	0.0160	0.7037	0.7711	0.0277	0.2542	0.1303
Leaves	0.0381	0.9362	0.8310	0.1223	0.6804	0.2585
Stalk	0.7840	0.0843	0.3677	0.0045	0.0084	0.0056
Reproductive				0.0114	0.0179	0.1158
Grain					-	-
			Magnesium			
Whole Plant	0.8933	0.6816	0.4631	0.0594	0.0002	0.3788
Leaves	0.7382	0.2231	0.4736	0.0257	<.0001	0.9423
Stalk	0.9412	0.6614	0.5083	0.2262	0.4612	0.0142
Reproductive				0.0060	0.0092	0.3040
Grain					0.3495	0.8412
			Sulfur			
Whole Plant	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Leaves	<.0001	0.0004	<.0001	<.0001	<.0001	<.0001
Stalk	0.3331	<.0001	<.0001	<.0001	<.0001	<.0001
Reproductive				<.0001	<.0001	0.0175
Grain					0.0017	<.0001

Table 12. Seasonal potassium accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	11 b†	44 b	83 b	109 c	150 c	132 c
MOP	12 a	45 b	85 b	121 b	161 b	148 b
POLY4:MOP	12 a	47 ab	88 b	135 a	170 a	159 a
POLY4	13 a	49 a	96 a	136 a	179 a	161 a
	Leaves					
UTC	8 b	32 b	68 b	65 c	61 c	23 c
MOP	9 a	33 ab	70 b	73 b	70 b	32 b
POLY4:MOP	9 a	33 ab	72 ab	83 a	75 a	38 a
POLY4	9 a	36 a	76 a	82 a	76 a	38 a
	Stalk					
UTC	3.0 b	11.8 b	14.8 b	14 b	15 c	26 b
MOP	3.2 ab	12.4 ab	15.4 ab	19 a	18 b	33 a
POLY4:MOP	3.4 a	13.5 a	16.3 ab	18 a	20 ab	35 a
POLY4	3.5 a	13.1 a	19.8 a	20 a	23 a	36 a
	Reproductive					
UTC	-	-	-	30 b	34 b	27 b
MOP	-	-	-	29 b	33 b	27 ab
POLY4:MOP	-	-	-	34 a	34 b	28 ab
POLY4	-	-	-	34 a	38 a	30 a
	Grain					
UTC	-	-	-	-	40 a	56 a
MOP	-	-	-	-	40 a	56 a
POLY4:MOP	-	-	-	-	41 a	58 a
POLY4	-	-	-	-	42 a	57 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 13. Seasonal calcium accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	2 b†	13 a	27 a	36 b	45 b	43 b
MOP	3 a	13 a	28 a	37 b	45 ab	46 a
POLY4:MOP	3 a	13 a	27 a	40 a	46 ab	45 ab
POLY4	3 a	13 a	28 a	36 b	47 a	47 a
	Leaves					
UTC	2.1 b	9.5 a	22.1 a	28.1 ab	33.3 a	33.5 b
MOP	2.4 a	9.4 a	23.0 a	27.9 b	33.9 a	35.2 ab
POLY4:MOP	2.4 a	9.7 a	23.0 a	30.4 a	33.5 a	34.8 ab
POLY4	2.4 a	9.4 a	23.1 a	27.4 b	34.5 a	36.7 a
	Stalk					
UTC	0.3 a	3.2 b	4.6 ab	5.3 b	6.6 b	5.8 b
MOP	0.3 a	3.5 ab	4.7 ab	6.5 a	7.5 a	6.8 a
POLY4:MOP	0.3 a	3.7 a	4.4 b	6.3 a	8.0 a	6.7 a
POLY4	0.3 a	3.4 ab	4.9 a	6.5 a	7.7 a	7.0 a
	Reproductive					
UTC	-	-	-	2.5 b	4.9 a	3.7 ab
MOP	-	-	-	2.2 b	4.0 b	4.2 a
POLY4:MOP	-	-	-	2.8 a	4.1 b	3.6 b
POLY4	-	-	-	2.3 b	5.1 a	3.5 b
	Grain					
UTC	-	-	-	-	-	-
MOP	-	-	-	-	-	-
POLY4:MOP	-	-	-	-	-	-
POLY4	-	-	-	-	-	-

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 14. Seasonal magnesium accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	2 a†	15 a	30 a	30 a	52 a	48 a
MOP	2 a	14 a	32 a	32 a	51 a	51 a
POLY4:MOP	2 a	14 a	30 a	30 a	46 b	49 a
POLY4	2 a	14 a	29 a	29 b	47 b	50 a
	Leaves					
UTC	1.7 a	10.1 a	21 a	24 a	29 a	23 a
MOP	1.7 a	9.4 ab	23 a	24 a	28 a	24 a
POLY4:MOP	1.8 a	9.1 b	21 a	24 a	23 b	23 a
POLY4	1.7 a	9.1 b	20 a	20 b	24 b	24 a
	Stalk					
UTC	0.3 a	4.9 a	8.7 a	10.9 b	11.3 a	8.5 b
MOP	0.3 a	5.0 a	9.1 a	12.0 a	12.3 a	10.9 a
POLY4:MOP	0.3 a	5.3 a	8.5 a	11.7 ab	12.1 a	10.2 a
POLY4	0.3 a	5.0 a	9.1 a	11.6 ab	11.8 a	10.0 a
	Reproductive					
UTC	-	-	-	4.7 a	5.6 a	3.6 ab
MOP	-	-	-	3.9 b	4.6 b	3.9 a
POLY4:MOP	-	-	-	4.7 a	4.6 b	3.7 ab
POLY4	-	-	-	4.3 a	5.1 ab	3.5 b
	Grain					
UTC	-	-	-	-	5.9 a	12.8 a
MOP	-	-	-	-	6.0 a	12.5 a
POLY4:MOP	-	-	-	-	6.1 a	12.4 a
POLY4	-	-	-	-	6.3 a	12.8 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 15. Seasonal sulfur accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	1.1 b†	4.8 b	8.8 b	12.0 b	16.9 c	18.9 c
MOP	1.1 b	4.5 b	8.3 b	11.4 b	17.1 c	20.0 b
POLY4:MOP	1.2 a	5.8 a	10.6 a	15.2 a	20.6 b	24.3 a
POLY4	1.2 a	5.7 b	11.0 a	14.8 a	21.6 a	24.8 a
	Leaves					
UTC	0.9 b	3.9 b	7.4 b	6.8 b	6.4 c	4.3 b
MOP	0.9 b	3.7 b	7.0 b	6.7 b	6.9 b	4.7 b
POLY4:MOP	1.0 a	4.7 a	8.8 a	8.8 a	8.1 a	6.0 a
POLY4	1.0 a	4.6 a	9.0 a	8.3 a	8.3 a	6.3 a
	Stalk					
UTC	0.15 b	0.9 b	1.4 b	1.9 b	1.7 b	1.2 c
MOP	0.15 ab	0.8 b	1.3 b	1.9 b	1.8 b	1.4 c
POLY4:MOP	0.16 ab	1.1 a	1.8 a	2.8 a	2.9 a	2.5 b
POLY4	0.17 a	1.1 a	2.0 a	2.9 a	3.0 a	2.7 a
	Reproductive					
UTC	-	-	-	3.3 b	2.4 bc	1.5 c
MOP	-	-	-	2.8 c	2.1 c	1.8 bc
POLY4:MOP	-	-	-	3.6 a	2.6 b	2.1 a
POLY4	-	-	-	3.6 a	3.0 a	2.0 ab
	Grain					
UTC	-	-	-	-	6.4 b	11.9 b
MOP	-	-	-	-	6.3 b	12.1 b
POLY4:MOP	-	-	-	-	7.0 a	13.7 a
POLY4	-	-	-	-	7.3 a	13.8 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

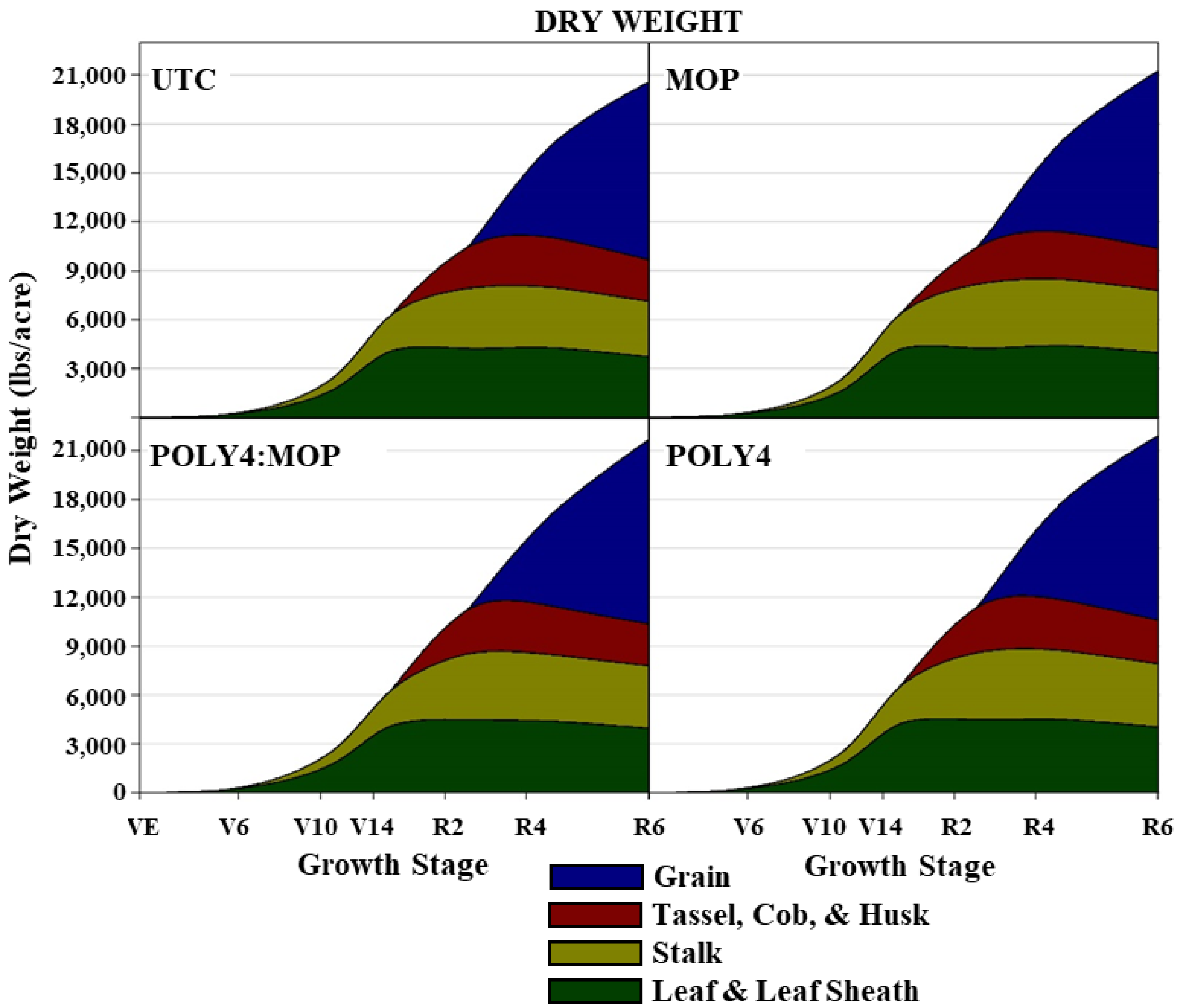

Figure 1. Seasonal accumulation and partitioning of dry weight resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

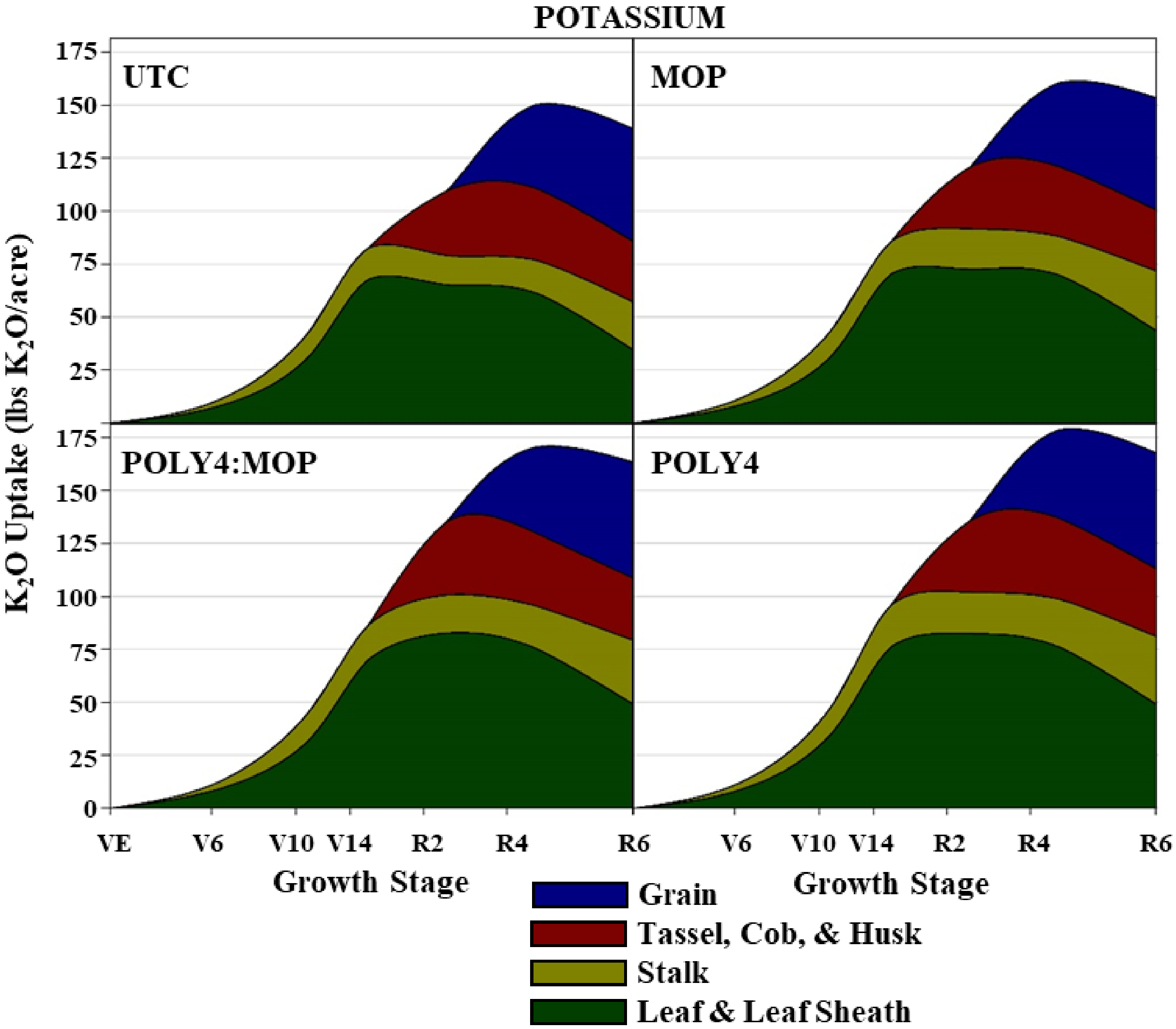

Figure 2. Seasonal accumulation and partitioning of potassium resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

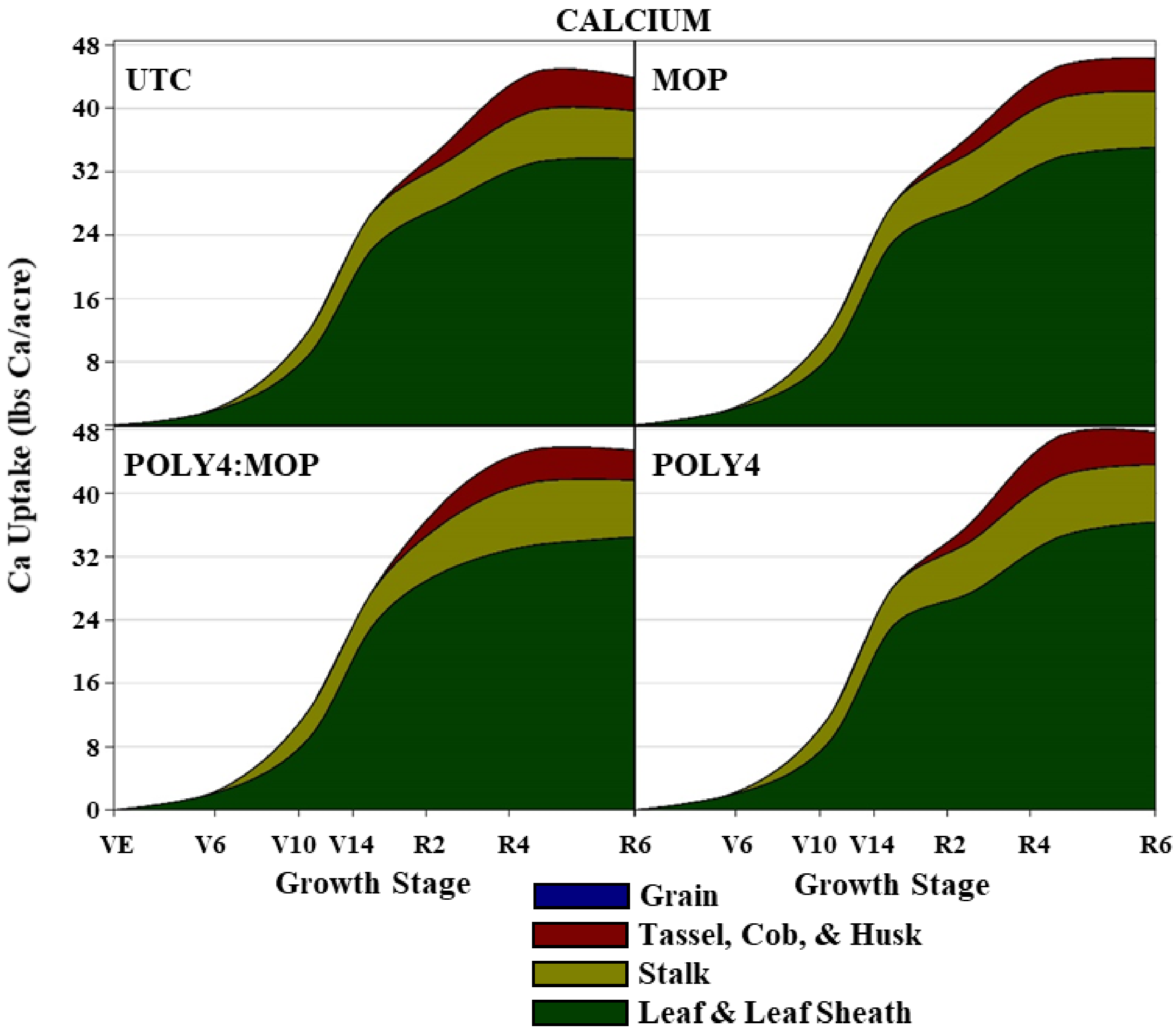

Figure 3. Seasonal accumulation and partitioning of calcium resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

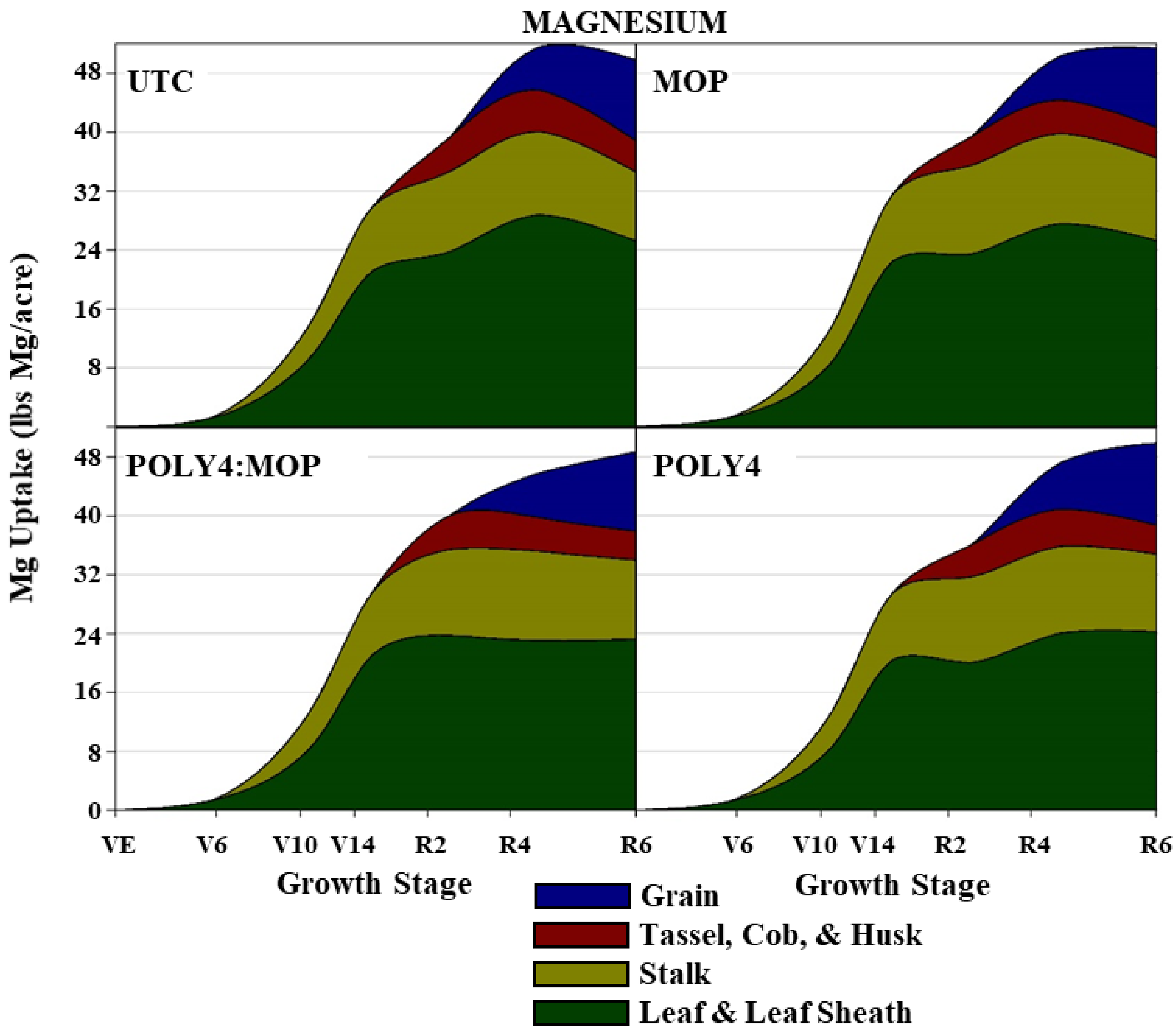

Figure 4. Seasonal accumulation and partitioning of magnesium resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

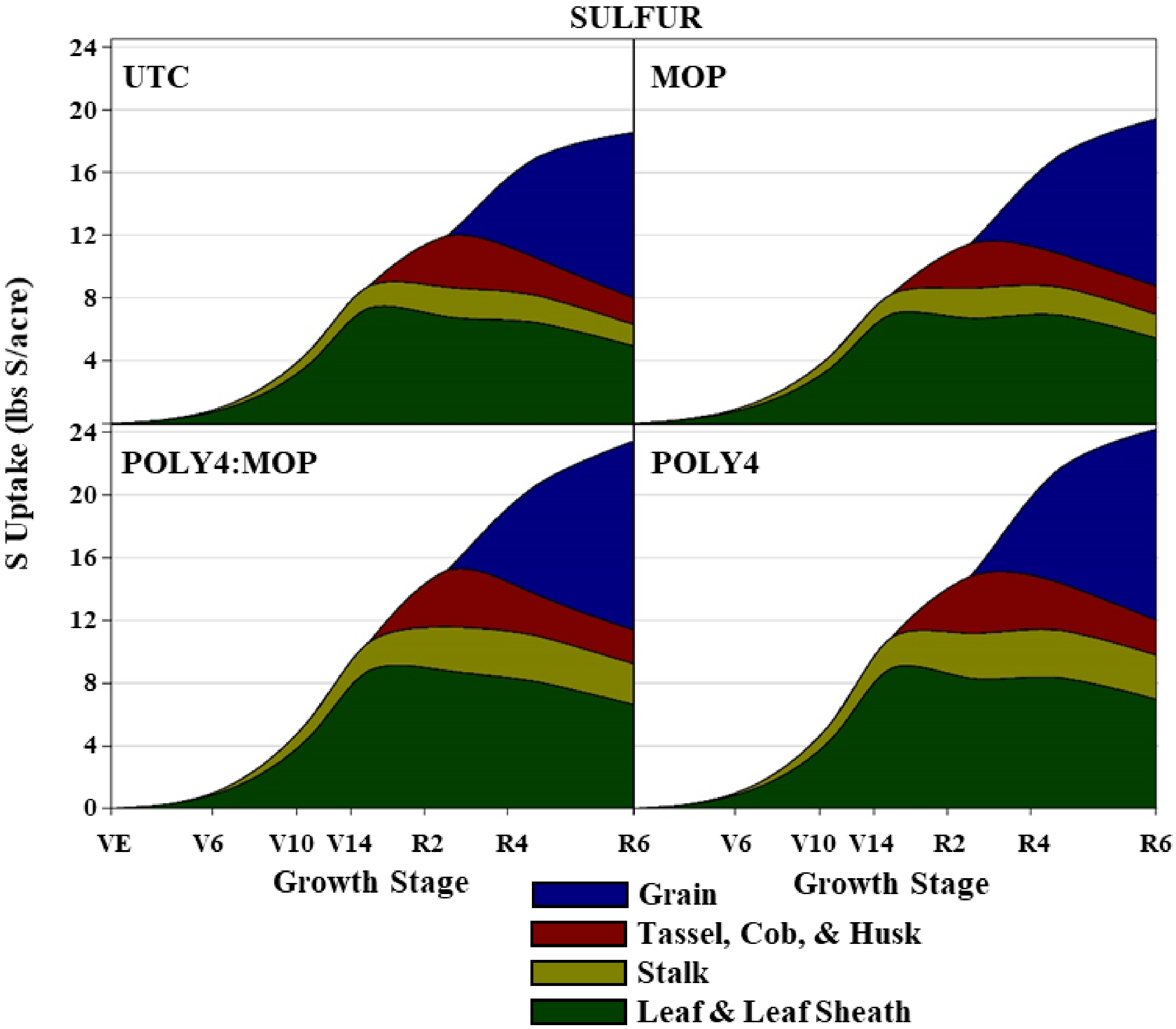

Figure 5. Seasonal accumulation and partitioning of sulfur resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

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APPENDIX A: SUPPLEMENTARY TABLES AND FIGURES

Table 16. Tests of potassium fertility treatment significance for average leaf nutrient concentrations of nitrogen and phosphorus by growth stage for corn grown at Champaign IL in 2017 and 2018.

Source of Variation	Growth Stage					
(Nutrient)	V6	V10	V14	R2	R4	R6
			P* > *F			
Nitrogen	0.0846	0.0230	0.0215	0.8949	0.3676	0.0189
Phosphorus	0.0418	0.0954	0.0610	0.5453	0.8093	0.3535

Table 17. Tests of potassium fertility treatment significance for average leaf nutrient concentration of nitrogen and phosphorus by growth stage for corn grown at Champaign IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
			%			
			Nitrogen			
UTC	4.55 a†	3.44 a	2.70 a	2.22 a	1.97 a	1.14 c
MOP	4.44 b	3.29 b	2.53 b	2.15 a	2.05 a	1.19 bc
POLY4:MOP	4.45 b	3.20 b	2.61 ab	2.19 a	2.09 a	1.26 ab
POLY4	4.48 ab	3.28 b	2.72 a	2.20 a	2.10 a	1.27 a
			Phosphorus			
UTC	0.41 a	0.35 a	0.30 a	0.25 a	0.21 a	0.09 a
MOP	0.40 ab	0.34 a	0.28 ab	0.24 a	0.21 a	0.10 a
POLY4:MOP	0.39 b	0.31 b	0.27 b	0.24 a	0.21 a	0.10 a
POLY4	0.39 b	0.34 ab	0.30 a	0.23 a	0.20 a	0.09 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 18. Tests of potassium fertility treatment significance for average nutrient accumulation of nitrogen and phosphorus by plant part at six growth stages for corn grown at Champaign IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
			Nitrogen			
Whole Plant	0.0327	0.0544	0.0243	0.1111	0.0152	0.0123
Leaves	0.0941	0.0629	0.0670	0.4950	0.0149	0.0198
Stalk	0.3742	0.2177	0.1918	0.1966	0.1752	0.0083
Reproductive				0.0005	0.1619	0.3350
Grain					0.1289	0.1024
			Phosphorus			
Whole Plant	0.1795	0.5742	0.0868	0.7492	0.5920	0.3650
Leaves	0.4817	0.5664	0.2118	0.7742	0.8805	0.0838
Stalk	0.6951	0.3224	0.0733	0.8444	0.3348	0.0008
Reproductive				0.0182	0.3613	0.0084
Grain					0.5322	0.7863

Table 19. Seasonal nitrogen accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	16 b†	76 a	136 ab	161 ab	205 b	210 b
MOP	16 b	69 b	130 b	154 b	210 b	221 a
POLY4:MOP	17 a	76 a	132 b	166 a	214 b	226 a
POLY4	17 a	75 a	142 a	168 a	223 a	229 a
	Leaves					
UTC	13.4 c	60 a	110 ab	98 a	84 b	41 b
MOP	13.6 bc	54 b	106 b	92 a	93 a	45 ab
POLY4:MOP	14.4 a	59 a	107 b	98 a	92 a	48 a
POLY4	14.2 ab	58 a	116 a	99 a	94 a	49 a
	Stalk					
UTC	2.9 a	16.4 ab	25.6 ab	26.1 b	18.5 b	15.2 b
MOP	2.8 a	15.3 b	23.9 b	27.2 ab	18.3 b	17.0 a
POLY4:MOP	2.9 a	16.8 a	24.5 ab	27.6 ab	19.4 ab	16.7 a
POLY4	3.1 a	16.5 ab	25.9 a	28.5 a	20.0 a	17.5 a
	Reproductive					
UTC	-	-	-	38 b	27 ab	9 a
MOP	-	-	-	35 c	26 b	9 a
POLY4:MOP	-	-	-	40 ab	28 ab	10 a
POLY4	-	-	-	41 a	30 a	10 a
	Grain					
UTC	-	-	-	-	75 ab	145 b
MOP	-	-	-	-	73 b	149 ab
POLY4:MOP	-	-	-	-	75 b	153 a
POLY4	-	-	-	-	79 a	151 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

Table 20. Seasonal phosphorus accumulation resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

	Growth Stage					
Treatment	V6	V10	V14	R2	R4	R6
	lb acre^{-1}					
	Whole Plant					
UTC	4 b†	19 a	34 a	49 a	68 a	79 a
MOP	4 ab	17 a	33 ab	48 a	70 a	83 a
POLY4:MOP	4 a	17 a	31 b	50 a	70 a	84 a
POLY4	4 a	18 a	35 a	49 a	71 a	83 a
	Leaves					
UTC	2.9 a	14.2 a	27.6 ab	24.7 a	20.5 a	6.7 b
MOP	2.9 a	13.3 a	26.8 ab	23.4 a	21.2 a	8.3 a
POLY4:MOP	3.0 a	13.0 a	25.4 b	24.6 a	20.7 a	8.5 a
POLY4	2.9 a	14.0 a	28.6 a	23.9 a	20.4 a	8.0 a
	Stalk					
UTC	0.9 a	4.5 a	6.6 a	10.8 a	5.7 b	2.4 c
MOP	0.9 a	4.1 a	5.8 b	11.4 a	5.9 ab	3.0 ab
POLY4:MOP	0.9 a	4.5 a	5.7 b	10.6 a	6.4 a	2.7 bc
POLY4	1.0 a	4.3 a	6.3 ab	10.9 a	6.2 ab	3.3 a
	Reproductive					
UTC	-	-	-	13.4 ab	7.5 a	2.8 c
MOP	-	-	-	12.7 b	7.5 a	3.2 bc
POLY4:MOP	-	-	-	14.4 a	7.6 a	4.1 a
POLY4	-	-	-	14.4 a	8.3 a	3.4 b
	Grain					
UTC	-	-	-	-	34.5 a	66.8 a
MOP	-	-	-	-	35.5 a	67.9 a
POLY4:MOP	-	-	-	-	35.5 a	69.8 a
POLY4	-	-	-	-	36.6 a	68.3 a

† Values followed by the same letter are not significantly different at ($P \leq 0.10$) within each growth stage and plant part.

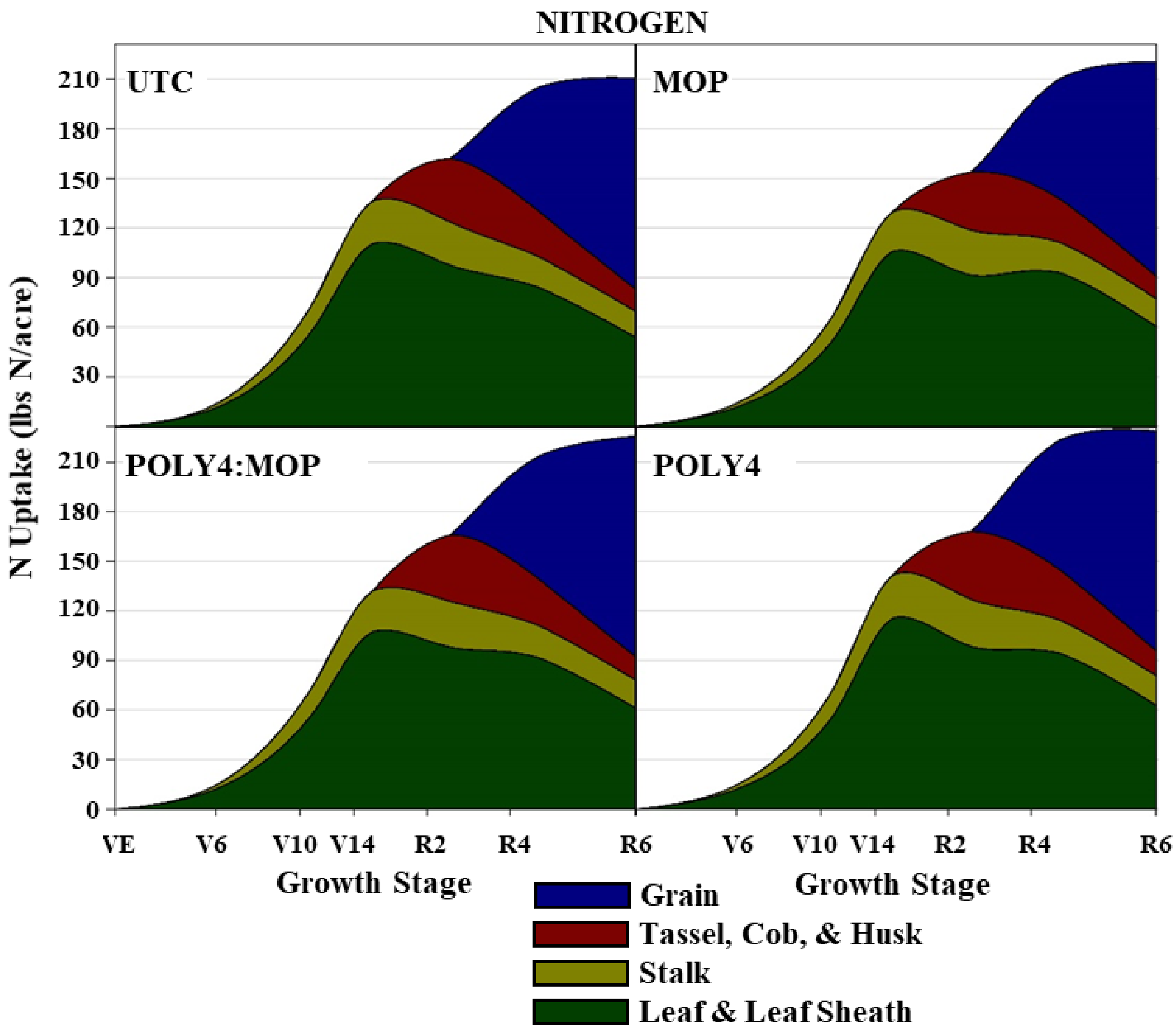

Figure 6. Seasonal accumulation and partitioning of nitrogen resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.

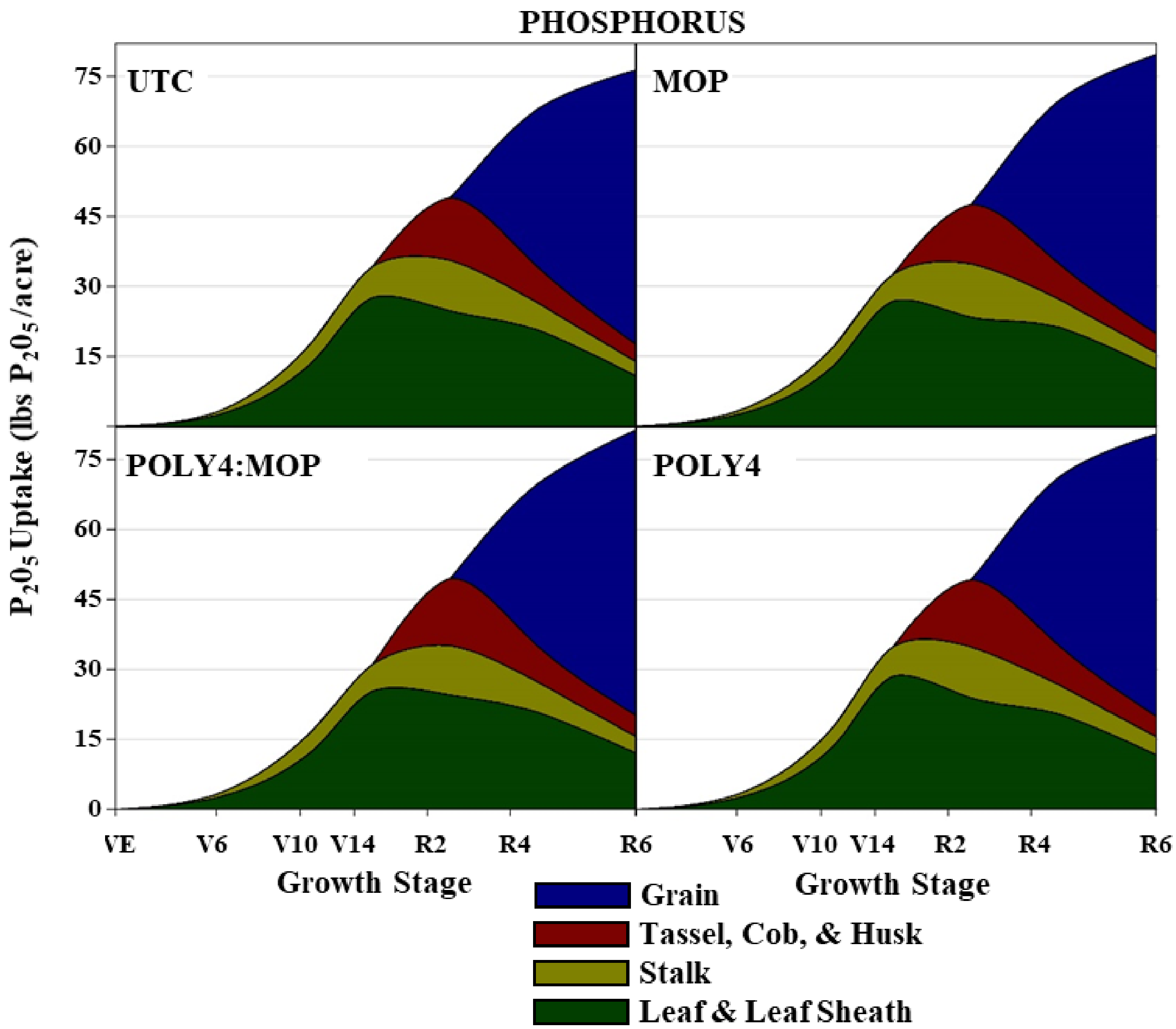

Figure 7. Seasonal accumulation and partitioning of phosphorus resulting from preplant potassium fertilizer treatments for corn grown at Champaign, IL in 2017 and 2018.